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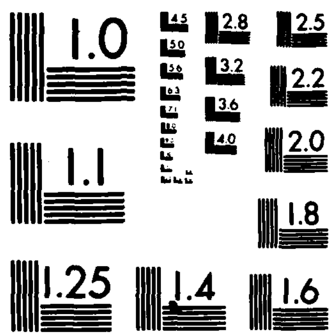
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DEVELOPMENT OF REFEREE FUELS FOR IMPROVED ARMY MULTIFUEL ENGINE DESIGN

INTERIM REPORT
BFLRF No. 172

By

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Initiation by the U.S. Army Tank-Automotive Command (TACOM) of the Advanced Integrated Propulsion System (AIPS) prompted the development of referee fuels that would (1) indicate to prospective engine/component developers the anticipated quality of fuels available when AIPS is fielded as part of the next main battle tank, and (2) a means for TACOM to ensure that new engines and components would be able to fully demonstrate a "multifuel capability." The work reported here resulted in the development of two referee fuels: Type I, a high-volatility, low-viscosity fuel; and Type II, a low-volatility, high-viscosity fuel, both having low cetane numbers. Future multifuel engine design and development work ~~will utilize~~ these referee fuels to ensure operation on a broad range of fuels that may become available.

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FOREWORD

This report was prepared at the Belvoir Fuels and Lubricants Research Facility (SwRI) located at Southwest Research Institute, San Antonio, TX, under Contract Nos. DAAK70-82-C-0001 and DAAK70-85-C-0007, for the period 1 January 1981 through 31 December 1985. Work was funded by the U.S. Army Belvoir Research, Development and Engineering Center, Ft. Belvoir, VA, with Mr. F.W. Schaekel (STRBE-VF) serving as contracting officer's representative. Project technical monitor was Mr. M.E. LePera, STRBE-VF.

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I. INTRODUCTION

The future availability of petroleum crude oil for processing into fuels that will meet current mobility fuels specifications is a continuing concern of the Department of Defense. It is anticipated that the refining industry must place increasing reliance on heavy petroleum crudes and synthetic crudes. Efficient utilization of these energy sources may require manufacturing fuels with properties that differ considerably from current fuels. As part of the defense mobility fuels action plan developed for the Department of Defense, a major thrust was to develop engine systems having a multifuel capability for utilizing a broad range of conventional and synthetic fuels. To develop these engine systems, it became necessary to establish referee fuels that could be employed during the engine design stages.

This report describes the efforts expended in developing these referee fuels and gives the reasons for establishing certain property limits.

II. BACKGROUND

Over the years, engine manufacturers have designed and built diesel engines based on fuels of average quality; however, in the early days of these engines no specifications were established for diesel fuels.(1)* Later, representatives of the engine manufacturers and of the petroleum industry met and outlined requirements for diesel fuels. The most important properties were considered to be ignition quality, cleanliness, and viscosity. Eventually fuel specifications were adopted that reportedly satisfied the requirements of the diesel engine.

Through selection of crudes and development of advanced refining processes, the manufacturing of clean-burning, high-ignition-quality, inexpensive fuels became widespread.

In the late 1950's, the U.S. Army decided to convert most of its mobility equipment from spark-ignition to compression-ignition engines. The initial

*Underscored numbers in parentheses refer to the references at the end of this report

approach was to develop a family of multifuel engines.(2,3) During the transition period, an effort was made to find a suitable diesel fuel with adequate availability without jeopardizing the supply of other essential fuels.(4) Between June 1958 and May 1983, a series of specifications were developed for a referee grade and an operational compression-ignition engine fuel which were as follows: MIL-F-45121 (Ord), Fuel Oil, Diesel, Referee Grade; MIL-F-45121A (Ord), Fuel Oil, Compression Ignition Engine, Referee Grade (CIE); MIL-F-45121B, Fuel, Compression Ignition and Turbine Engine, Referee (CITE.R) (5); MIL-F-46005 (MR), Fuel, Compression Ignition Engine (CIE); and MIL-F-46005A (MR), Fuel, Compression Ignition and Turbine Engine (CITE).(6) All these fuels were similar in boiling range, but had variations in other properties. The final versions of the CITE and CITE.R fuels encompassed most of the properties of aircraft turbine fuel JP-4 which was a broad boiling range fuel and reported to be in plentiful supply.(1)

A referee fuel is for use during the research, development, and proof-testing of military engines and related systems to ensure their satisfactory operation when fielded. Prior to the introduction of referee fuels, engine development was focused on using primary design fuels. Four fuel classifications are defined in Army Regulation 703-1 (7) as follows:

(1) Primary Fuel. A fuel that permits full design performance.

(2) Alternate Fuel. A fuel that provides performance equal to the primary fuel, but may be a restricted item of supply in tactical areas or has environmental limitations. No degradation of performance or service life occurs as a result of the use of an alternate fuel within the prescribed operational range.

(3) Alternative Fuel. Any liquid fuel, refined from a naturally occurring or synthetically derived crude, that can be substituted for readily available petroleum standard fuels.

(4) Emergency Fuel. A fuel used when the primary or alternate fuel is not available. The use of an emergency fuel may result in increased maintenance and/or reduced engine life. Severe performance degradation is permissible when an emergency fuel is used, but it must not destroy the materiel within the operating period prescribed by the engine designer.

A multifuel engine developed in Germany at Maschinenfabrik Augsburg-Nurnberg AG (MAN) was the forerunner of the Continental LD-465 engine adopted by the Army.(8) This and other Army engines were evaluated extensively using wide boiling range fuels which included the referee grade compression-ignition fuel (CIE) (MIL-F-45121A).(9)

Another multifuel engine developed was the Texaco Controlled-Combustion System (TCCS), which was evaluated with three fuels: a combat gasoline referee grade (the forerunner of MIL-G-46015), a CITE fuel referee grade (MIL-F-45121B), and a No. 2 diesel fuel.(10) A 100° to 600°F (38° to 315°C) boiling range fuel for use with the TCCS was proposed as a means of conserving energy.(11) The system has no octane or cetane requirements; therefore, the refinery would need to produce only one broad distillation range mobility fuel.

The fuel proposed for the Army's multifuel engine was a wide boiling range fuel known as compression-ignition and turbine engine (CITE) fuel, described earlier. MIL-F-45121B was the referee grade CITE fuel, and MIL-F-46005A was the CITE fuel intended for field use. However, other compression-ignition engines in the Military system such as the two-cycle engines would not operate well, if at all, on this fuel. A decision was subsequently made within the Army early in 1970 not to support development of a family of multifuel engines designed to utilize CITE fuel; therefore, the CITE fuel specification, MIL-F-46005A (MR) was cancelled on 28 July 1970. (NOTE: The referee grade MIL-F-45121B had been cancelled earlier on 27 December 1968). The CITE.R fuel, MIL-F-45121B, was used by AVCO Lycoming for development and proof-testing of Army aircraft turbine engines during the 1960-1970 period.

Since distillate fuels were plentiful in the 1960's and could be tailored to engine requirements, interest in multifuel engines waned considerably until the oil embargo of 1973. The vulnerability of the fuel supply caused renewed interest in multifuel engines, increased recognition of procurement problems, and requests for waivers of certain requirements of specification fuels.

The quality of crude oils worldwide has been declining over the last few years, so that more extensive refining is required to produce satisfactory products. Cycle stocks from catalytic cracking processes are more frequently being used in diesel fuels. Another factor impacting on the quality of diesel fuel is the impetus to utilize more of the residual portion of the barrel. As coal, nuclear power, natural gas, and other energy sources are increasingly used for electric power generation and coal and natural gas use increases in process plant steam-raising installations, the proportion of residual fuel oil required from the barrel is diminishing. To utilize this surplus residual fuel, it is being converted by cracking and possibly coking to distillates, primarily to increase the yield of diesel fuel. Therefore, the chances of having marginal diesel fuels for military use, particularly in periods of high demand, are increasing.

Investigators evaluating "synthetic" fuels derived from shale or coal often treat these materials severely so that they end up with properties that meet requirements of current specifications for diesel fuel. Expensive treatment is required to achieve this. Efficient utilization of crudes, both petroleum and synthetic, dictates that fuels be produced with a minimum of upgrading.

Other wide boiling fuels have been proposed as referee fuels intended to represent the types of fuels that may be generally available in the future. In 1982, an Experimental Referee Broadened-Specification (ERBS) aviation turbine fuel was proposed for turbine engine development work by National Aeronautics and Space Administration Lewis Research Center (NASA).(12) In work conducted for the Department of Energy at Southwest Research Institute, a broadcut high refinery yield fuel was investigated.(13)

To increase future supplies of diesel fuel in Canada, it was proposed to add virgin naphthas to the normal diesel fuel blends.(14) With the exception of a low cetane number fuel and one with high volatility, all fuels performed satisfactorily in a variety of engines. Work conducted in England showed that extending diesel fuels with 25 percent of various shale, coal, or vegetation-derived products is normally feasible.(15)

Referee diesel fuel meeting MIL-F-46162C, Fuel Oil, Diesel, Referee Grade, (16) is currently required to be used during engine systems development, testing and evaluation in accordance with AR 703-1 (7) and AR 70-56.(17) The fuel procured under this specification represents a worst case condition of a fuel still meeting requirements of Federal Specification VV-F-800C, Oil, Diesel, Grade DF-2, and is currently being utilized at U.S. Army Test and Evaluation Command (TECOM) testing facilities and within U.S. Army Tank-Automotive Command (TACOM).(18)

A letter dated 18 June 1986 to TACOM from the U.S. Army Belvoir Research, Development and Engineering Center, Fuels and Lubricants Division, transmitted a "Position Statement Governing Use of MIL-F-46162 Referee Grade Diesel Fuel."(19) This position statement, included in the Appendix of this report, documents the need for requiring the referee grade fuel in research, development and proof testing of all new generation compression-ignition engines and diesel-powered auxiliary units.

In August 1982, TACOM initiated an Advance Intergrated Propulsion System (AIPS) structured to provide a power package for future heavy combat vehicles.(20,21) One of the target technical goals of the AIPS program is to develop engines with a wide fuel tolerance. Therefore, the work reported herein was initiated to (1) provide guidance to prospective component/engine developers as to the anticipated quality of fuels that would be available when AIPS is fielded as part of the next main tank (i.e., the late 1990's), and (2) provide a means for TACOM to ensure that these engines and components would be able to fully demonstrate a "multifuel capability."

Fig. 1 depicts the broad range of fuels that conceivably could be used in mobility applications provided that future engine systems could be designed to operate on either gases, liquid, or solid fuels. The current engine design and proof testing fuel is MIL-F-46162C. The work being reported here covers the development of the "first generation" Type I and Type II fuels shown as "near term 1983-1990" in Fig. 1.

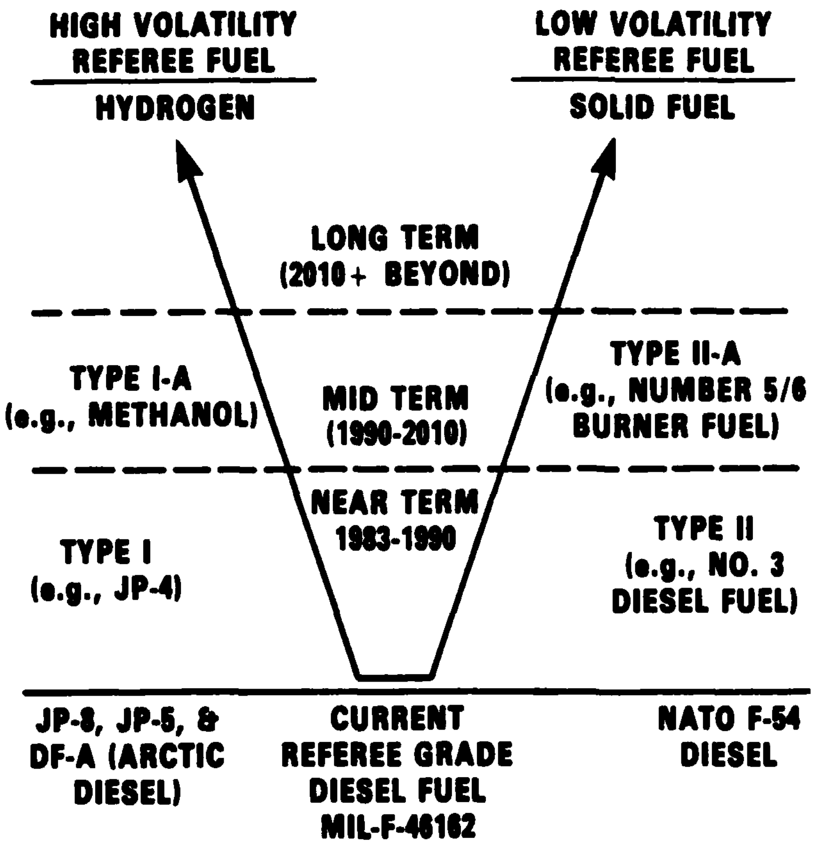


Figure 1. Projected Trends in Multifuel Engine Fuel Tolerance

III. OBJECTIVES

The objectives of this program were to develop a referee fuel description which, when used during the engine design and development process, would ensure that these engines, when fielded, would operate successfully on a wide variety of distillate-type fuels. After such a fuel was described, sources for engine research quantities of fuel were developed.

IV. APPROACH

In order to develop referee fuels, a number of factors were considered. Current trends in distillate fuel properties, fuel demand, and refinery configuration were evaluated to develop future fuel property and availability estimates. Current Army compression-ignition engine designs and their fuel limitations were also examined. Table 1 is a summary listing of different engine types currently existing within the Army's inventory. In a referee fuel, there are a number of important fuel properties which one would like to have at the "worst" acceptable value (i.e., almost or at the specification limit). Usually this is not possible, so current engine limitations were used to develop a priority list of important fuel properties.

Based on these studies, referee fuel specifications were formulated and several refiners contacted to determine if fuel blends meeting these require-

TABLE 1. Engine Systems Used in Army Ground and Aviation Equipment

	Spark-Ignition	
Two-Cycle	Air-Cooled	Normally-Aspirated
Two-Cycle	Liquid-Cooled	Normally-Aspirated (Marine Application)
Four-Cycle	Liquid-Cooled	Normally-Aspirated
Four-Cycle	Air-Cooled	Normally-Aspirated and Turbocharged (Marine and Aviation Applications)
	Compression-Ignition	
Two-Cycle	Liquid-Cooled	Normally-Aspirated and Turbocharged
Four-Cycle	Liquid-Cooled	Normally-Aspirated, Turbocharged and Multi-fuel
Four-Cycle	Air-Cooled	Turbocharged
	Gas Turbine	
Gas Turbine	Turbo-Shaft/ Turbo-Prop	Aviation and Ground

ments could be produced in adequate quantities. As necessary, the specifications were adjusted to ensure producibility.

V. DISCUSSION OF RESULTS

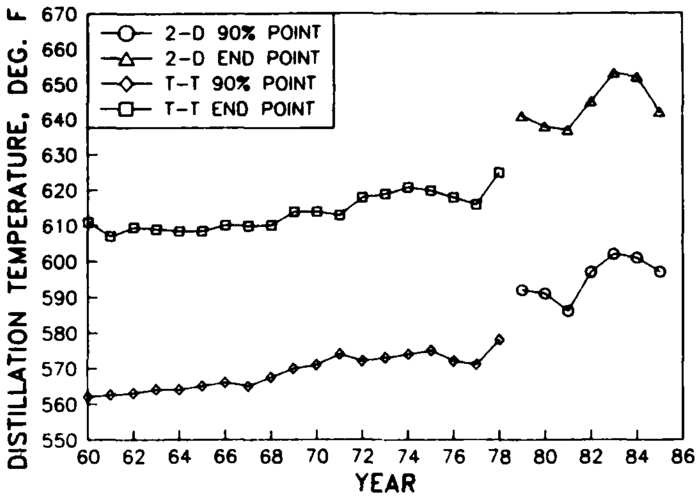
The Motor Vehicles Manufacturers Association (MVMA) conducts semi-annual surveys of diesel fuels, analyzing samples taken from service station pumps in 17 cities across the nation. Based on these surveys for 1980, 1981, 1982, and 1983, the quality of the U.S. diesel fuel has been declining. During this period, the average cetane number of commercial ASTM D 975 2-D diesel fuel went from 47 to 45. More significantly, the number of surveyed samples

that were below the minimum 40 cetane number were 0 in 1980, 6 percent in 1981, 8 percent in 1982, and 11 percent in 1983. The sulfur content limit for ASTM D 975 2-D diesel fuel is 0.5 percent maximum. In 1980, 1 percent of the samples surveyed were above the sulfur content limit, while in 1983, 10 percent were found to be above the limit.

Annual surveys of diesel fuels obtained from refinery locations published by the National Institute for Petroleum and Energy Research (NIPER) for the American Petroleum Institute (22) show that the average distillation temperatures at 90 percent recovered and end point have been increasing as shown in Fig. 2; cetane numbers have been decreasing as shown in Fig. 3; and kinematic viscosities at 100°F (38°C) have been increasing as seen in Fig. 4. However, it is noted that a reversal of these trends ocurred in 1985. From 1960 to 1982, the fuels whose properties are shown in these figures classified as T-T fuels (trucks-tractors) were mostly 2-D fuels but also included some 1-D fuels. From 1970 on, the 2-D fuels were reported separately.

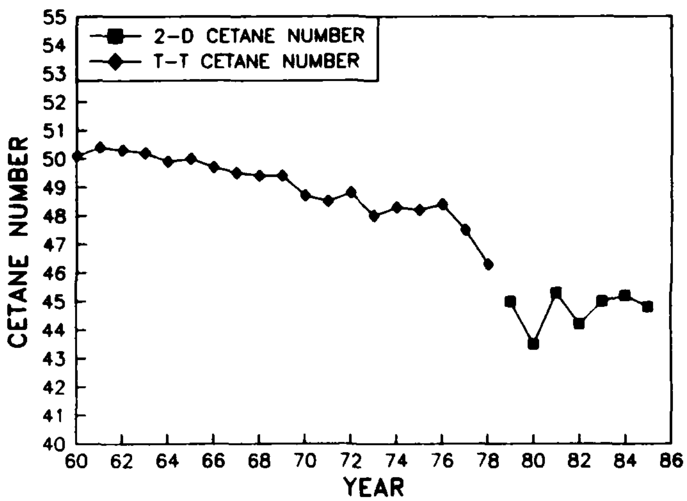
A recent report which projected general trends in fuel properties concluded that diesel fuels in the U.S. are suffering a decrease in quality as measured by gravity, aniline point, carbon residue, and cetane number and that the changes in these properties can be attributed to a trend toward heavier distillation ranges as well as decreasing crude oil quality.(23) The report also stated that crude oil quality is rapidly decreasing in the world at about 1 °API each 10-year period. The U.S. is suffering a greater quality decrease, while crude oil quality in Europe is decreasing less rapidly.

U.S. gasoline demand is projected to decline from 43 percent of total products to 32 percent by 2000, while distillates and jet fuel will rise from 25 percent to 32 percent. Total light product demand will decrease from 68 percent to 64 percent of total. Resid demand will vary from 12 to 15 percent of total product.(23) In refinery construction, large percentage gains are planned in the U.S. for thermal cracking, catalytic hydrocracking and hydrogen manufacturing. Worldwide refinery construction plans emphasize heavy crude refining.



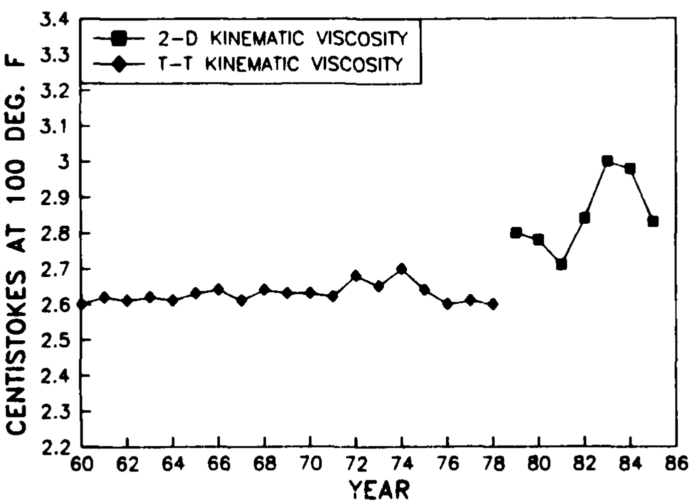
SOURCE: "DIESEL FUEL OILS, 1985" API/NIPER-142PPS85/5

Figure 2. Average Distillation Temperatures at 90% Recovered and End Point



SOURCE: "DIESEL FUEL OILS, 1985" API/NIPER-142PPS85/5

Figure 3. Average Cetane Numbers



SOURCE: "DIESEL FUEL OILS, 1985" API/NIPER-142PPS85/5

Figure 4. Kinematic Viscosities at 100°F (38°C)

Results of research conducted at Belvoir Fuels and Lubricants Research Facility (BFLRF) at Southwest Research Institute and elsewhere have shown that fuel properties that affect the ability of a compression-ignition engine to run satisfactorily for short periods of time are cetane number, volatility, and viscosity.(24) For longer operation periods, fuel properties such as distillation end point, carbon residue, and sulfur content become more important. These properties have little impact on short-term operations such as low-temperature startability, power, and fuel economy. Since the referee fuels being developed here were seen as development fuels for engine research, it was felt that these durability-impacting properties were less important than those affecting short-term operation. Therefore, although properties such as carbon residue, sulfur content, ash levels, and particulate contamination were specified at levels near the upper end of the current fuel specification, no attempt was made to either project the trend of the properties nor to set them at overly stressful levels. Many current engines are limited to use of fuels with properties of VV-F-800C diesel fuels which include a minimum cetane number of 40, kinematic viscosities at 40°C in the range 1.1 to 4.1 cSt and boiling ranges of about 150°C initial to 370°C final boiling point.

Consideration of a broadcut fuel for engine development work that would encompass the volatility of a wide boiling range aircraft turbine fuel (JP-4) as well as a No. 4 diesel fuel was discarded in favor of two fuels with different properties. Since a single referee fuel could not provide a range of viscosities and other properties required for multifuel engine development, the two referee fuels were proposed. The Type I and Type II not only represent the extremes in volatility and viscosity that may be available in future fuels, but also encompass current and those future fuels having intermediate properties. The cetane number of the referee grade fuels as well as viscosities and volatility can be controlled by using special blending stocks when preparing these fuels. Refinery process streams, such as light cycle oil, have high viscosity, low volatility, and low cetane number. Others, such as BTX bottoms or high aromatic naphtha, have low viscosity, high volatility, and low cetane number. These and other materials can be used to prepare these referee grade fuels.

Many different types of distillate petroleum fuels are currently available and are expected to be available well into the future. Fig. 5 compares the boiling ranges in terms of distillation by ASTM D 86 of most of these mobility fuels to the boiling ranges of the proposed Type I and Type II experimental referee grade fuels. These two referee fuels together delineate the range of fuels that would be considered acceptable alternatives to VV-F-800.

Gasoline-type fuels are expected to continue to be widely available in the future and methanol may become more available. However, these fuels have not been considered in the proposed referee fuel descriptions for the following reasons:

1. The engine design changes that would be required to accommodate the relatively high volatility and low cetane number of gasoline and methanol would be extreme and would create severe penalties in terms of performance and economy for the engine systems. The low energy content of methanol would severely reduce the engine's maximum power.

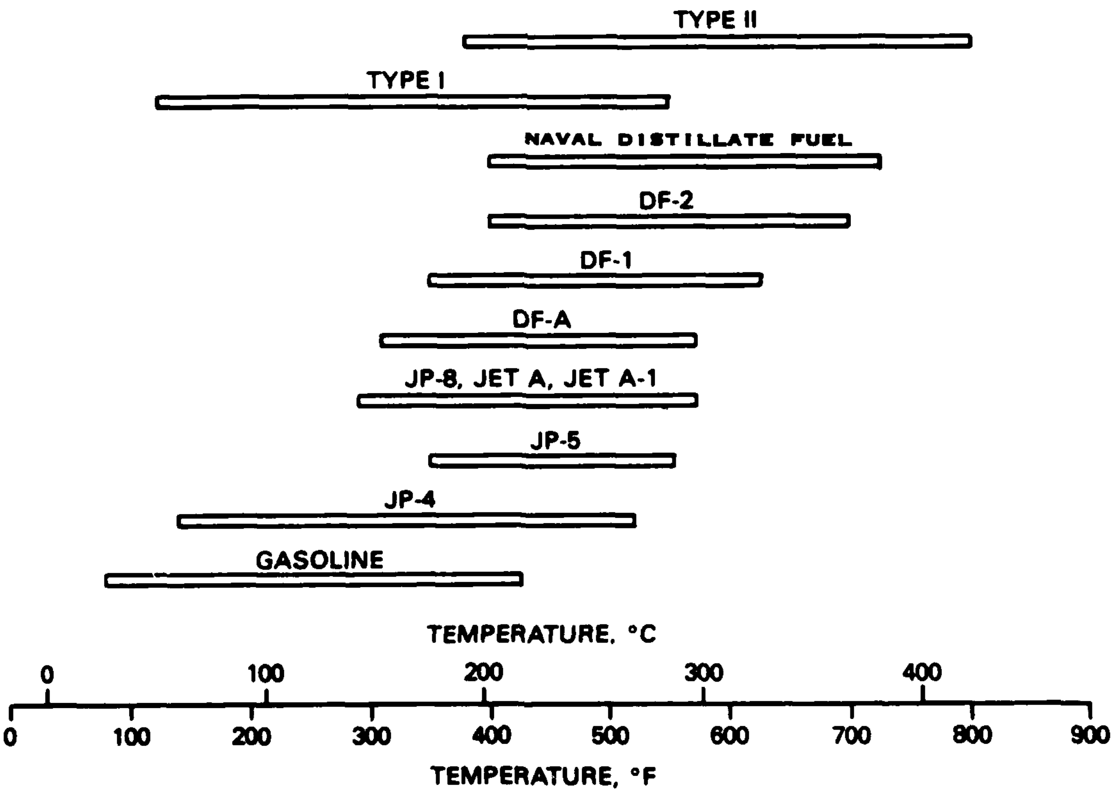


Figure 5. Boiling Ranges of Experimental Referee Fuels and Current Specification Fuels

2. Switch loading between the high-volatility gasoline/methanol fuels and the much lower volatility diesel-type fuels would create a potentially hazardous condition in which explosive fuel/air mixtures would be present in fuel transfer, dispensing, refueling, and vehicle storage operations.

3. If vehicles are designed for occasional use of the lighter fuels, then a potential for a constant on-board hazard exists during combat. Therefore, gasoline and methanol should be considered only as emergency fuels.

The Type I high-volatility fuel was designed using the obsolete compression ignition and turbine engine fuel (CITE) as a model. The more significant differences between the two fuels are that the CITE fuel had a minimum cetane number of 37, while Type I has a range of 20 to 30, and the CITE fuel had maximum limits for aromatics and olefins of 25 and 5 percent, respectively, which are not included in the Type I requirement. This fuel is also in the same boiling range as JP-4. Table 2 gives the requirements for the low-volatility Type I fuels, and all the refiners and blenders contacted indicated no difficulty in providing this type of fuel. Three fuels from three sources, including one that was blended at BFLRF, are also shown in Table 2.

Since the Type I fuel requirements are based on the specification for CITE fuel, the use of this fuel should also be considered as a referee fuel for future development of Army aircraft turbine engines.

The development of the Type II low-volatility experimental referee grade fuel was less straightforward. The various stages in the development of the requirements for this fuel are shown in Table 3. The first set of requirements was found to be unrealistic because the minimum API gravity of 28 degrees was inconsistent with the boiling range limits tentatively selected. The second set of requirements corrected those inconsistencies; however, the samples blended to meet those requirements consistently had a kinematic viscosity at 40°C of approximately 3 cSt, the low end of the specified range which was felt to be inadequate for a referee fuel. Table 4 contains the

TABLE 2. Experimental Referee Fuel Type I, High-Volatility

Properties	Requirements	AL-10999-F	AL-13660-F	AL-13704-F
RVP, kPa	6.9 to 34.5	15.2	17.9	15.2
(psi)	(1 to 5)	2.2	2.6	2.2
Density at 15°C, kg/L	0.750 to 0.801	0.784	0.772	0.775
Gravity, °API	45 to 57	49.0	51.7	51.1
Distillation, °C (°F)				
10 vol% recovered	127 (260) max	103 (218)	87 (188)	96 (204)
50 vol% recovered	191 (375) max	164 (327)	140 (287)	128 (263)
90 vol% recovered	232 (450) max	227 (440)	213 (415)	231 (447)
End point	288 (550) max	258 (497)	254 (489)	260 (500)
Cetane Number	20 to 30	28	28	<u>36</u>*
Carbon Residue on 10% bottoms, mass%	0.2 max	0.08	0.09	0.08
K. vis. at 40°C, (104°F), cSt	0.9 max	0.76	0.67	0.85
Sulfur, mass%	0.5 max	0.01	<0.01	<0.01
Ash, mass%	0.01 max	none	none	none
Freezing Point, °C (°F)	−40 (−40) max	−41 (−42)	<−66 (<−87)	−58 (−73)
Thermal Stability				
JFTOT at 260°C (500°F)				
Pressure, in. Hg	25 max	0	0	0
Tube Rating	<3	1	1	2
Hydrogen, mass%	report	13.45	13.52	13.8
Particulate Contaminants, mg/L	10 max	0.3	2.2	0.5
Copper Corrosion at 50°C (122°F)	No. 1 max	1a	1a	1a

* = Underlined value failed to meet requirements.

TABLE 3. Changes in Requirements for Type II Low-Volatility Fuel

Properties	First Set	Second Set	Third Set
Density at 15°C, kg/L	0.887 max	0.934 max	0.934 max
Gravity, °API	28 min	20 min	20 min
Distillation, °C (°F)			
50 vol% recovered	260 (500) max	288 (550) max	report
90 vol% recovered	316-371 (600-700)	316-371 (600-700)	316-385 (600-725)
Flash Point, °C (°F)	54 (130) min	54 (130) min	54 (130) min
Cetane Number	35 max	35 max	35 max
Cetane Index	-	-	35 max
Carbon Residue on 10% bottoms, mass%	0.40 max	0.40 max	0.40 max
K. Vis. at 40°C (104°F), cSt	4 to 9	3 to 9	7.0 to 9.0
Sulfur, mass%	0.8 to 1.2*	0.8 to 1.2*	0.8 to 1.2
Ash, mass%	0.05 max	0.05 max	0.05 max
Cloud Point, °C (°F)	-7 (+20) max	-7 (+20) max	-7 (+20) max
Accelerated Stability, mg/100 mL	1.5 max	1.5 max	1.5 max
Particulate Contaminants	10	10	10
Copper Corrosion at 50°C (122°F)	1 max	1 max	1 max

* = Naturally occurring sulfur is preferable but addition of tert-butyl disulfide to reach the specified sulfur content is permissible.

TABLE 4. Properties of Candidate Type II Fuels With Low-Viscosity

Properties	Requirements	AL-11930-F	AL-11972-F
Density at 15 kg/L	0.934 max	0.9089	0.9124
Gravity, °AP	20 min	24.1	23.5
Distillation, °C (°F)			
10 vol% recovered	NR*	233 (451)	238 (458)
50 vol% recovered	(550) max	269 (516)	269 (517)
90 vol% recovered	316-371 (600 -700)	324 (616)	318 (604)
End point	NR	358 (677)	350 (662)
Flash Point, °C (°F)	54 (130) min	68 (154)	83 (182)
Cetane Number	35 max	33.0	34.4
Cetane Index	NR	32	31
Carbon Residue on 10% bottoms, mass%	0.40 max	0.46**	0.47
K. Vis. at 40°C, cSt	3-9	2.97	2.82
Sulfur, mass%	0.8-1.2	1.16	1.21
Ash, mass%	0.05 max	0	<0.001
Cloud Point, °C (°F)	-7 (20) max	-17 (+1)	-17 (+2)
Accelerated Stability, mg/100 mL	1.5 max	3.8	0.13
Particulate Contaminants, mg/L	10 max	5.3	0.7
Copper Corrosion at 50°C	1 max	1a	1a

*NR = No Requirement
** = Underlined values failed to meet requirements.

properties of two blends that were prepared to meet the requirements in Set 2.

It was believed that in the design of engines with multifuel capabilities, the ability of these engines to handle fuels with high viscosities should be stressed. Therefore, the range of 7 to 9 cSt at 40°C, which is higher than the viscosity range for current No. 2 diesel fuels, was specified as shown in Table 5. In order to limit the viscosity at 40°C to a minimum of 7 cSt, it was necessary to relax the distillation requirements. Thus, the requirement at 50 percent recovered was removed and the 90 percent recovered temperature range was expanded.

Table 5 also contains the properties of two fuels blended by refiners to meet the latest requirements of Type II experimental referee grade fuel.

These proposed referee fuels are being used in the design of multifuel compression-ignition engines as well as in the design of gas turbine engines. Therefore, additional properties of these fuels become important to engine designers, i.e., gross and net heat of combustion, hydrogen content, and aromatics content. These properties for the Type I fuel are generally known, since this fuel is quite similar to JP-4. The Type II fuel, however, is very different than any currently available fuel. Therefore, these properties were measured for two samples of Type II fuels received from different sources. These values are listed in Table 6.

The experimental referee grade fuels Type I and Type II were finalized with properties as shown in Table 7. The adoption of these referee fuels for research, development, and proof-testing of new and future military engines is fully supported by both TACOM and the Project Manager-Mobile Electric Power.

Samples and procurements of Type I fuels shown in Table 2 have approached or exceeded the upper cetane number limit of 30 for this fuel. Suggestions from TACOM indicated that this level of cetane number would not adequately stress the intended multifuel capability of an engine. Therefore, it has been

TABLE 5. Properties of Candidate Type II Fuels With High Viscosity

Property	Requirements	AL-13851	AL-13857
Gravity, °API	20 min	21.7	23.5
Distillation, °C (°F)			
IBP	NR*	205 (401)	227 (440)
10% recovered	NR	252 (485)	264 (508)
50% recovered	report	319 (607)	317 (602)
90% recovered	316 to 385 (600 to 725)	367 (693)	359 (679)
End point	NR	385 (725)	377 (711)
Flash Point, °C (°F)	54 (130) min	97 (206)	ND**
Cetane Number	35 max	39.2	35
Cetane Index	NR	35.7	38
Carbon Residue on 10% bottoms, mass%	0.40 max	0.16	0.30
K. Vis. at 40°C (104°F), cSt	7.0 to 9.0	7.32	7.29
Sulfur, mass% +	0.80 to 1.20	0.96	0.46
Ash, mass%	0.05 max	<0.01	ND
Cloud Point, (°C) °F	-7 (+20) max	-8 (+17)	-10 (+14)
Pour Point, (°C) °F	NR	-10 (+14)	-16 (+3)
Accelerated Stability, mg/100 mL	1.5 max	0.25	ND
Particulate Content, mg/L	10 max	0.8	2.2 mg/ 500 mL
Cu Corrosion at 50°C	1 max	1a	ND

*NR = Not required
**ND = Not determined.
*** = Underlined values failed to meet requirement limits.
\+ = Naturally occurring sulfur is preferable, but addition of tert-butyl disulfide to reach the specified sulfur content is permissible.

TABLE 6. Elemental Composition and Combustion Properties of Type II Fuels

Properties	AL-13851-F	AL-14055-F
Carbon, mass%	87.41	86.94
Hydrogen, mass%	11.50	12.24
Gross Heat of Combustion,		
MJ/kg	44.032	44.482
Btu/lb	18,931	19,124
Net Heat of Combustion,		
MJ/kg	41.593	41.885
Btu/lb	17,882	18,007

Table 7. Requirements for Experimental Referee Grade Fuels

Property	Type I Requirements	Type II Requirements
RVP, kPa	6.9 to 34.5	NR*
(psi)	(1 to 5)	NR
Density at 15°C, kg/L	0.750 to 0.801	0.934 max
Gravity, °API	45 to 57	20 min
Distillation, °C (°F)		
10% recovered	127 max (260 max)	report
50% recovered	NR	
50% recovered	191 max (375 max)	report
90% recovered	232 max (450 max)	report
End Point	288 max (550 max)	316 to 385 (600 to 725)
Cetane Number	20 to 30	35 max
Flash point, °C (°F)	NR	54 min (130 min)
Carbon residue on 10% bottoms, mass %	0.20 max	0.40 max
K. Vis. at 40°C (104°F), cSt	0.9 max	7.0 to 9.0
Sulfur, mass %	0.5 max	0.80 to 1.20**
Ash, mass %	0.01 max	0.05 max
Cloud point, °C (°F)	NR	-7 (+20)
Freezing point, °C (°F)	-40 max (-40 max)	NR
Thermal stability		
JFTOT at 260 °C (500°F)		NR
Pressure drop, in. Hg	25 max	NR
Tube rating	3	NR
Hydrogen, mass %	report	NR
Particulate contaminants, mg/L	10 max	10 max
Accelerated stability, mg/100 mL	NR	1.5 max
Copper corrosion at 50°C (122°F)	1 max	1 max

*NR = No Requirement

** = Naturally occurring sulfur is preferred, but addition of TBDS is permitted. Not less than half of the total sulfur in the finished fuel shall be naturally occurring.

suggested that the cetane number limits for the Type I fuel be changed to 20 minimum and 25 maximum. It may be possible to adjust the cetane number as suggested by using aromatic or highly branched paraffins as blending stocks.

VI. CONCLUSIONS AND RECOMMENDATIONS

Referee grade fuels of two types as described in this report can be provided to engine designers and manufacturers so that future engines for military application will have multifuel capabilities. It is recommended that the suggested change to the Type I fuel be investigated further before incorporation into the requirements for this fuel. It is also recommended that the U.S. Army Aviation Systems Command (AVSCOM) consider use of Type I as a referee fuel for future development of Army aircraft turbine engines.

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APPENDIX

POSITION STATEMENT GOVERNING USE OF MIL-F-46162 REFEREE GRADE DIESEL FUEL

POSITION STATEMENT GOVERNING USE OF MIL-F-46162 REFEREE GRADE DIESEL FUEL

Background

Military Specification MIL-F-46162C(ME), Fuel, Diesel, Referee Grade, was developed, as stated in the specification, "... for use in research, development and proof testing of all compression-ignition engines, diesel-powered auxiliary units, gas turbine engine driven ground vehicles and mobile electric power generators, and other fuel-handling supply items designed to operate with tactical grades of diesel fuel conforming to VV-F-800." The same specification defines the referee grade fuel "... as diesel fuel representing the minimal or marginal quality level which can be procured under Federal Specification VV-F-800 Fuel Oil, Diesel while meeting all of its requirements." Except for requiring higher levels of allowable fuel sulfur than are typically found within the NATO Theater, it is designed to be equivalent to the quality of OCONUS distillate production or that production available in times of national emergency.

The development of engines and engine components (i.e., fuel injection equipment, fuel filters, etc.) with the referee grade fuel is important to ensure that when the vehicles or equipment are fielded, they will satisfactorily operate on the lowest quality of fuel that may be available on the market. Engines and components designed and developed around a high quality level fuel may not operate satisfactorily when subjected to a VV-F-800 fuel of marginal quality. Army regulation 703-1[(1)] recognizes and also reinforces the NATO requirement to use a referee quality diesel fuel such as MIL-F-46162 in endurance and qualification testing of automotive systems. This requirement is cited in the Allied Engine Publication No. 5 (AEP-5) of NATO Armaments Committee AC/225.

Worldwide Distillate Fuel Trends

The quality of crude oils worldwide has been declining over the last few years, so that more extensive refining is required to produce satisfactory products. Cycle

[(1)]AR703-1, "Coal and Petroleum Products Supply and Management Activities," August 1985; paragraph 2.3.c.b.

stocks from catalytic cracking processes are more frequently being used in blending diesel fuels. Another factor impacting on the quality of diesel fuel is the impetus to utilize more of the residual portion of the barrel in addition to the trend of refining heavier crude feedstocks. As coal, nuclear power, natural gas, and other energy sources are increasingly used for electric power generation and in process plant installations, the proportion of residual fuel oil required from the barrel is diminishing. To utilize this surplus residual fuel, it is being converted by cracking and possibly coking to distillates, primarily to increase the yield of the diesel fuel pool. Therefore, the chances of having marginal diesel fuels for military use, particularly in periods of high demand, are increasing.

Based on the semi-annual Motor Vehicle Manufacturers Association (MVMA) automotive fuel surveys for 1980, 1981, 1982, and 1983, the quality of the U.S. diesel fuel has been declining. During this period, the average cetane number of commercial grade diesel fuel (ASTM D-975) went from 47 to 45. More significantly, the number of surveyed samples that were below the minimum 40 cetane number were 0 in 1980, 6 percent in 1981, 8 percent in 1982, and 11 percent in 1983. The sulfur content limit for commercial diesel fuel is 0.5 percent maximum. In 1980, 1 percent of the samples survey were above the sulfur content limit, while in 1983, 10 percent were found to be above the limit.

Annual refinery surveys of diesel fuels published by the National Institute for Petroleum and Energy Research (NIPER) also shows that the average distillation temperatures at 90% recovered and end point for commercial diesel fuels have been increasing over the last few years. However, in 1985 these properties did decrease somewhat. A listing of typical sulfur levels for diesel fuels in countries throughout the world was presented recently by an international oil company. The values, ranging from a low of 0.14% S to a high of 1.00%, are shown in Table 1.

In view of the above trends, all new engine systems and components must be designed and tested with appropriate consideration given to this declining fuel quality. Failure to recognize this requirement will only serve to further intensify the numbers of fuel-related problems that occur with the fielding of new vehicles and equipment.

TABLE 1. SULFUR LEVELS

Country	Sulfur, mass%
AUSTRALIA	0.14
BAHRAIN	0.84
EGYPT	0.67
HONG KONG	0.5
INDONESIA	0.5
KENYA	0.97
KOREA	0.39 (0.98)
MALAYSIA (Peninsular)	0.96
NEW ZEALAND	0.39
PAKISTAN	1.00
PHILIPPINES	1.00
SAUDI ARABIA	0.8
SINGAPORE	0.46
SOUTH AFRICA	0.48
TAIWAN	0.5 (1.00)
THAILAND	0.90
UNITED ARAB AMIRATES (DUBAI)	0.80

This picture of declining diesel fuel quality is of great concern, for this indicates that during periods of sustained military mobilization, the quality of diesel fuel available to the US Forces is expected to deteriorate quickly from the current levels.

During periods of high military fuel demand, refinery yield of middle distillate (jet fuel and diesel fuel) will need to be maximized. This, in all likelihood, will be partly achieved through reductions in the level of processing, further increase in use of cracking processes, and use of lower quality (i.e., heavier) crude stocks than

currently acceptable. This will result in reduced distillate fuel quality. The increased middle-distillate demand will have even greater impacts on OCONUS areas where refineries are less flexible than in the U.S. or European areas. The Army is particularly concerned because of their need to operate equipment worldwide on a short notice; that is, operate on locally produced fuels. Table 2 compares the current properties of the MIL-F-46162C referee diesel fuel with the requirements and typical inspection properties for VV-F-800C CONUS and OCONUS diesel fuels.

An additional recognition of this decline in diesel/distillate fuel quality has been evidenced within the Coordinating European Council (CEC) and their promulgation of CEC Referee Fuels.[2] Their reference fuels, like our referee fuel, are needed so that "...engine builders can design their hardware to operate satisfactorily on the great majority of fuels that are likely to be available in the civilian marketplace." The CEC Reference Fuel RF-72-T-84 reflects a diesel fuel of anticipated quality in the 1990 timeframe. Key inspection property limits for this reference fuel are as follows:

Cetane Number	40 to 42
Sulfur, wt%	0.3 to 1.5

Equipment Impacts

Changes in fuel properties can have both short- and long-term effects on diesel engine operation. Fuel properties, such as viscosity, cetane number, and cloud point, can affect starting and available power. These and other properties, such as the 90% distillation point, sulfur content, and ash levels, may cause engine deterioration that requires longer periods before the effects become noticeable.

While it is not possible to hold all fuel properties at their worst specification-constrained levels at once, the referee fuel specification attempts to strike a balance that will stress both the short- and long-term engine response. It is therefore intended for proof testing of engine systems and components in all

[2] Second International Symposium on the Performance Evaluation of Automotive Fuels and Lubricants, Paper EF-1 entitled "The Design and Philosophy of CEC Reference Fuels," Volume 3, Coordinating European Council, Wolfsburg, GE, 5-7 June 1985.

TABLE 2. CONVENTIONAL DF-2 VERSUS MIL-F-46162C REFEREE FUEL

Property	VV-F-800C, Grade DF-2 Requirements CONUS	OCONUS	Typical Values	MIL-F-46162C(ME) Requirements	Typical Values
Density, kg/L at 15°C	Report	0.815 to 0.860	0.8505	Report	0.8609
Flash point, °C	52 min	56 min	74	52 min	62
Cloud point, °C	Local*	Local	-2	-13 max	-18
Pour point, °C	Report	Local	-3	-18 max	-23
Kinematic viscosity at 40°C, cSt	1.9 to 4.1	(1.8 to 9.5)**	2.56(3.85)	1.9 to 4.1	2.90
Distillation, °C:					
Initial boiling point	NR***	NR	177	Report	190
10% recovered	NR	NR	220	220 min	228
50% recovered	Report	Report	261	255 to 305	263
90% recovered	338 max	357 max	310	310 to 360	330
95% recovered	NR	NR	321	315 to 365	349
End Point	370 max	370 max	337	385 max	375
Residue, vol%	3 max	3 max	1.0	3 max	1.0
Carbon residue on 10% bottoms, wt%	0.35 max	0.20 max	0.13	0.20 max	0.13
Sulfur, wt%	0.50 max	0.70 max	0.27	0.95 to 1.05	1.01
Copper strip corrosion, 3 hours at 50°C, ASTM classification	3 max	1 max	1A	1 max	1A
Ash, wt%	0.01 max	0.02 max	<0.001	0.02 max	<0.001
Accelerated stability, total insolubles, mg/100 mL	1.5 max	1.5 max	0.17	1.5 max	1.5
Neutralization No., TAN	NR	0.10	0.04	0.2 max	0.03
Aromatics, vol%	NR	NR	—	Report	40+
Net heat of combustion, BTU/lb	NR	NR	—	Report	18,110
Particulate contamination, mg/L	10	10	0.8	10 max	5.3
Cetane number	40	45	50	37 to 43	43
Free water and particulate contamination	NR	NR	—	Pass	Pass

* Local requirements vary; see Appendix A, VV-F-800C.

** Kinematic viscosity at 20°C.

*** None Required.

\+ Determined by HPLC Method.

applications where VV-F-800 diesel fuel would normally be used. Use of the referee fuel is not required for evaluation of components not in contact with the fuel, combustion byproducts, or the engine lubricant.

Such testing helps assure the Army that the engine or component designer has adequately considered the impact that fuel property variations allowed within VV-F-800 will have on their equipment and has taken appropriate steps to deal with these fuel-related design aspects.

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DEPARTMENT OF THE NAVY

CDR
NAVAL AIR PROPULSION CENTER
ATTN: PE-33 (MR D'ORAZIO) 1
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CDR
NAVAL SEA SYSTEMS CMD
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CDR
DAVID TAYLOR NAVAL SHIP R&D CTR
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CODE 2831 1
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PROJ MGR, M60 TANK DEVELOPMENT
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US ARMY TANK-AUTOMOTIVE COMMAND (TACOM)
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DEPARTMENT OF THE NAVY
HQ, US MARINE CORPS
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NAVAL RESEARCH LABORATORY
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OFFICE OF THE CHIEF OF NAVAL RESEARCH
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DEPARTMENT OF THE AIR FORCE

HQ, USAF
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CDR
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LAB
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WRIGHT-PATTERSON AFB OH 45433

CDR
SAN ANTONIO AIR LOGISTICS
CTR
ATTN: SAALC/SFT (MR MAKRIS) 1
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OTHER GOVERNMENT AGENCIES

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CE-151
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ENVIRONMENTAL PROTECTION
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AIR POLLUTION CONTROL 1
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